Published October 3, 2014

Journal of Environmental Quality SPECIAL SECTION

PHOSPHORUS FATE, MANAGEMENT, AND MODELING IN ARTIFICIALLY DRAINED SYSTEMS

Contributions of Systematic Tile Drainage to Watershed-Scale Phosphorus Transport

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Abstract

Phosphorus (P) transport from agricultural fields continues to be a focal point for addressing harmful algal blooms and nuisance algae in freshwater systems throughout the world. In humid, poorly drained regions, attention has turned to P delivery through subsurface tile drainage. However, research on the contributions of tile drainage to watershed-scale P losses is limited. The objective of this study was to evaluate long-term P movement through tile drainage and its manifestation at the watershed outlet. Discharge data and associated P concentrations were collected for 8 yr (2005–2012) from six tile drains and from the watershed outlet of a headwater watershed within the Upper Big Walnut Creek watershed in central Ohio. Results showed that tile drainage accounted for 47% of the discharge, 48% of the dissolved P, and 40% of the total P exported from the watershed. Average annual total P loss from the watershed was 0.98 kg ha^{-1}, and annual total P loss from the six tile drains was 0.48 kg ha^{-1}. Phosphorus loads in tile and watershed discharge tended to be greater in the winter, spring, and fall, whereas P concentrations were greatest in the summer. Over the 8-yr study, P transported in tile drains represented <2% of typical application rates in this watershed, but >90% of all measured concentrations exceeded recommended levels (0.03 mg L^{-1}) for minimizing harmful algal blooms and nuisance algae. Thus, the results of this study show that in systematically tile-drained headwater watersheds, the amount of P delivered to surface waters via tile drains cannot be dismissed. Given the amount of P loss relative to typical application rates, development and implementation of best management practices (BMPs) must jointly consider economic and environmental benefits. Specifically, implementation of BMPs should focus on late fall, winter, and early spring seasons when most P loading occurs.

Eutrophication continues to be a major natural resource concern affecting marine and freshwater estuaries around the globe. Phosphorus (P) is often the limiting nutrient for nuisance algal blooms in freshwater systems (Sharpley et al., 1994). Over the last several decades, point sources of P delivery have been addressed in an effort to reduce accelerated eutrophication (Jarvie et al., 2013). More recent attention has focused on understanding diffuse or nonpoint sources of P; specifically, the role of agriculture on P delivery has been examined (Jarvie et al., 2013; Kleinman et al., 2011). Agricultural delivery of P may be exacerbated by drainage channels and subsurface tile drains (Sharpley et al., 2013). Phosphorus losses in subsurface tile drains were once thought to be negligible (e.g., Logan et al., 1980), but since the mid-1990s, it has been established that tile drainage is a significant pathway for P transport to surface waters (e.g., Kinley et al., 2007; Sims et al., 1998), a process that is further intensified through preferential flow (e.g., Simard et al., 2000).

Tile drainage is a common and necessary practice for crop production agriculture in the humid, poorly drained regions of the midwestern United States and Canada (Skaggs et al., 1994). An estimated 37% of cropland in the midwestern United States benefits from subsurface tile drainage (Zucker and Brown, 1998). However, work by Blann et al. (2009) indicates that the extent of tile drainage is likely significantly greater. The modified hydrologic regime that results from the installation of tile drainage facilitates the vertical movement of nutrients through the soil (i.e., greater infiltration capacity) and provides a direct connection from the field to nearby water bodies. Thus, P that reaches the tile drain can be carried from a much larger part of the landscape than would otherwise be possible solely through surface runoff (Heathwaite and Dils, 2000).

End-of-tile P concentrations have been shown in some instances to exceed current and proposed designated use recommendations (Sims et al., 1998). Several studies have reported that P concentrations in tile drainage vary seasonally (Gelbrecht et al., 2005; Eastman et al., 2010) and increase with increasing discharge (Gentry et al., 2007). Phosphorus losses in tile drainage are generally dominated by dissolved P (e.g., Kinley et al., 2007; Dils and Heathwaite, 1999), but particulate

J. Environ. Qual.
doi:10.2134/jeq2014.04.0149
Received 4 Apr. 2014.
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USDA–ARS, 590 Woody Hayes Dr., Columbus, OH 43210. Assigned to Associate Editor Carl Bolster.

Abbreviations: DRP, dissolved reactive phosphorus; FWM, flow-weighted mean; TP, total phosphorus.

P movement in tile drainage can be substantial, especially in cases where preferential flow paths develop (Vidon and Cuadra, 2011). It has also been observed that surface runoff rarely occurs on tile-drained fields (Macrae et al., 2007); therefore, total annual P losses (surface + tile) from a tile-drained field may be dominated by losses in tile drainage (Algoazany et al., 2007).

Surface and subsurface P losses have been measured and quantified at the plot and field scale, but the effect of tile drainage on P export at larger scales has not been evaluated. To better understand how tile drainage affects downstream water quality, information on P transport is needed at field and watershed scales. This study presents 8 yr (2005–2012) of continuous tile and watershed discharge and water quality data from a systematically tile-drained headwater watershed in central Ohio. This is one of the first studies to assess the integrated effects of tile drainage on the magnitude and timing of watershed P transport over a substantial timeframe through simultaneous monitoring of P delivery from all tile drains within the watershed and at the watershed outlet. The objective of this study was to quantify the monthly, seasonal, and annual contributions (concentrations and loading) of P transport through subsurface drainage in a headwater watershed and to relate those losses to losses measured at the watershed outlet. Specifically, the questions to be answered were: (i) Is the magnitude and temporal variability of P delivered via the tile system significant when compared with losses measured at the watershed outlet? and (ii) How do annual and seasonal tile and watershed concentrations compare with concentrations recommended to prevent eutrophic conditions?

Materials and Methods

Site Description

The experimental site selected for this study is a subwatershed of the Upper Big Walnut Creek watershed (King et al., 2008). The subwatershed was designated as watershed B and has a drainage area of 389 ha (Fig. 1). The drainage area is primarily comprised of two soil types: a somewhat poorly drained Bennington silt loam (52.9%) and a very poorly drained Pewamo clay loam (46.2%) (Table 1). Land use in watershed B is characterized by 86% agriculture, 6% woodland, and 8% urban/farmstead. The cropland is primarily in a corn–soybean rotation using rotational tillage (i.e., no-till beans into corn stubble and a disk chisel operation before corn planting). Soil fertility is generally managed with the corn crop. Based on crop management records obtained through farmer surveys from 2004 through 2008, P fertilizer in the watershed is generally broadcast and incorporated just before corn planting or injected at the time of corn planting. Typically, no commercial P application is made before soybean production, but in fall of 2007, poultry litter was applied to approximately 40% of the agricultural land within the watershed after soybean harvest. Approximately 80% of the watershed drainage area is systematically tile drained, with laterals positioned on 15-m center spacing at a depth of approximately 0.9 m. Two surface inlets (one located in a grassed waterway and the other in a roadside ditch) drain into the tile network (Fig. 1). The estimated average age of the tile is >50 yr, and the tile appeared to function normally throughout the study.

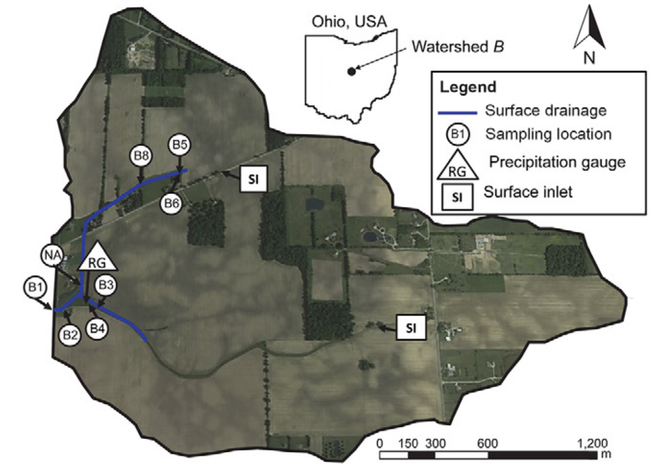

Fig. 1. Study watershed showing location of surface and subsurface sampling locations (e.g., B1), nonfunctioning tile (NA), precipitation gauge (RG), and surface inlet locations (SI). Site B1 was the location of the watershed outlet. Sites B2, B3, B4, B5, B6, and B8 were tile drain outlets.

The watershed is located in the humid continental, hot summer climatic region of the United States. The climate provides for approximately 160 growing days per year, generally lasting from late April to mid-October. Thunderstorms during the spring and summer generally produce short duration intense rainfalls. The normal (30-yr average) rainfall near the southwest portion of the watershed is 985 mm (NCDC, 2014). Moisture in the form of frozen precipitation or snow averages 500 mm annually and occurs primarily from December to March (NCDC, 2014).

Table 1. Sampling site characteristics for all monitoring locations within watershed B including estimated drainage area, average land slope, and soil series.†

Site	Description‡	Control volume	Drainage area	Slope	Soil series§	
					Bennington	Pewamo
			ha	m m^{-1}	——— % ———	
B1	watershed outlet	Parshall flume (2.4 m)	389	0.0087	52.9	46.2
B2	field tile	compound weir (0.3 m)	13.8	0.0086	71.9	28.1
B3	county main	H-flume (1 m)	211.6	0.0069	37.3	62.8
B4	field tile	compound weir (0.3 m)	14.9	0.0076	52.2	47.8
B5	tile main	H-flume (0.6 m)	22	0.0083	40.8	59.2
B6	tile main	H-flume (0.6 m)	49	0.0097	43.6	53.2
B8	field tile	compound weir (0.3 m)	7	0.0093	86.3	13.7

† Adapted from King et al. (2014).

‡ Diameter of tile drains: field tile, 0.2 m; tile main, 0.4 m; County main, 0.6 m.

§ Centerburg soil series is also found within the drainage area for sites B1 (0.9%) and B6 (3.2%).

Data Collection

Discharge and water quality instrumentation was installed in 2004 at all functioning surface and subsurface drainage pathways in watershed B. The surface outlet of the watershed, B1, was instrumented with a 2.4-m Parshall flume for hydrologic measurements (Table 1). The flume was instrumented with an Isco (Teledyne Isco) 4230 bubbler meter to measure stage. Stage measurements were recorded on a 10-min interval throughout the year. From 1 March to 15 December, water samples at the watershed outlet were collected with an Isco 6712 automated water sampler. Surface water samples at the watershed outlet were collected on a 6-h interval and composited weekly (composite of 28, 75-mL aliquots). Samples were collected weekly and stored at 4°C until analysis. When freezing air temperatures prevented the use of automated water samplers (16 Dec.–28 Feb.), weekly grab samples (1 L) were collected.

Each working tile outlet (n = 6 total) within the watershed was also instrumented for collecting discharge and water quality. One tile outlet, draining approximately 6 ha, was not functional at the start of the study and was not instrumented (designated as NA in Fig. 1). The tile was repaired in 2009 and is now functional; however, no instrumentation was installed on this tile outlet, and no samples were collected. The instrumented tiles ranged in diameter from 0.2 to 0.6 m, with contributing areas ranging from 7 to 211 ha (Table 1). Each tile outlet was initially instrumented with an Isco round orifice weir or an H-flume to maintain a constant control volume. All Isco weirs were replaced with compound weirs (Thel-Mar Co.) during the first 2 yr of the study to improve accuracy at low flows. The weir inserts create a damming effect that could lead to sediment deposition behind the weir and inhibit the function of the weir. However, no evidence of deposition that would create a functionality issue was observed. Each tile outlet was instrumented with an Isco 4230 bubbler meter to record stage and an Isco 6712 automated water sampler for collecting water samples. Isco 2150 area velocity sensors were installed in the drainage outlet pipes to aid discharge calculations when the pipes were submerged. Samples were collected from the tile on a 6-h interval and composited weekly (composite of 28 75-mL aliquots). Like the watershed outlet, weekly grab samples during the period from 16 December to 28 February were used to supplement automated sample collection.

Precipitation was measured on site using a dual approach. An Isco 674 tipping bucket rain gauge and a NovaLynx 260–2510 standard rain gauge were placed in the watershed near the outlets of tiles B3 and B4. Tipping bucket measurements were recorded on a 10-min interval and provided a rainfall distribution for each event. Tipping bucket amounts for each precipitation event were corrected using the volumetric depth collected with the standard gauge. Annually, the volume of water collected through the tipping bucket was approximately 10 to 15% less than that measured with the standard gauge. Precipitation events were defined as any event with a precipitation amount ≥6.35 mm separated by at least 6 h with no precipitation. Thus, it was possible to have more than one rainfall event occur on the same day.

Phosphorus Analysis

All samples were handled according to USEPA method 365.1 for P analysis (USEPA, 1983). Samples were stored below 4°C and analyzed within 28 d. Samples were vacuum filtered through a 0.45-μm pore diameter membrane filter for analysis of dissolved reactive P (DRP). Dissolved reactive P concentrations were determined colorimetrically by flow injection analysis using a QuikChem 8000 FIA Automated Ion Analyzer (Lachat Instruments) and application of the ascorbic acid reduction method (Parsons et al., 1984). The method detection limit for DRP was 0.003 mg L^{-1}. Total P (TP) analyses were performed on unfiltered samples after alkaline persulfate oxidation with subsequent determination of DRP (Koroleff, 1983).

Calculations and Statistical Approach

Discharge was calculated for each site using the 10-min measured stage and applying the stage–discharge relationship specific for the control volume (ISCO, 2006). In the case of submergence, area velocity data collected from the site were used to estimate discharge. A combination of baseflow and event flow was used to calculate watershed and tile discharge. Watershed baseflow was estimated daily using the local minimum method (Pettyjohn and Henning, 1979) within the Hydrograph Separation Program (Sloto and Crouse, 1996). Discharge rates were aggregated to daily, monthly, and annual volumes. Discharge volumes from individual tile outlets were summed to provide total tile discharge. Total discharge is expressed as volumetric depth (mm), which was calculated by dividing the discharge volume by the contributing area.

The contributing area of the watershed is 389 ha, and the estimated tile contributing area is 319 ha (Table 1). The extent of tile drainage associated with each tile outlet was determined using the Delaware County Ohio Auditor's 2010 1-ft resolution color orthophoto and existing tile plans on record with the Delaware County Soil and Water Conservation District. With the exception of B2, the contributing areas for each tile were encased by the watershed surface boundary. Approximately half (6 ha) of the contributing area for the B2 tile exists outside the watershed surface boundary.

Dissolved reactive P and TP loads were calculated by multiplying the analyte concentration by the measured water volume for that respective sample. The volume of water associated with any one sample was determined using the midpoint approach (i.e., the temporal midpoint between each sample was determined, and the volume of water was calculated for that time duration). The analyte concentration was assumed to be representative over the sampling interval. Tile loads were calculated as the summation of all measured tile sites. Flow-weighted mean (FWM) concentrations were calculated by dividing the respective load (tile or watershed) by the measured volume of water for the time interval of interest.

The contribution of tile drainage to watershed discharge, DRP, and TP loading was determined as the mean of the monthly fractions for each respective parameter. For example, the fraction of watershed discharge accounted for in subsurface tile drainage was determined by first calculating the fraction of watershed discharge represented by tile drainage for each month of the measured period (n = 96) and calculating the average of those values. The fraction of TP as DRP for watershed outlet (n = 865) and tile drainage (n = 2332) was calculated in a similar manner by calculating the average fraction measured for each water sample collected during the study period. Linear regression was used to examine the relationship between tile drainage and watershed discharge and P losses and to determine the relationship between TP and DRP in tile drainage and watershed discharge. Monthly data were divided into four seasons: winter (Jan.–Mar.), spring (Apr.–June), summer (July–Sept.), and fall (Oct.–Dec.). Analysis of variance was conducted on seasonal FWM P concentrations and P loads to determine if there were differences between seasons. The original dataset was skewed to the right, similar to most water quality data sets. To meet the assumption of normally distributed data for the ANOVA, data were log transformed before analysis. After the log transformation, data were considered normally distributed according to the Shapiro-Wilk normality test. When significant, all pairwise comparisons were analyzed using the Tukey post hoc test. All statistical analyses were conducted using R statistical software (R Development Core Team, 2011), and a probability level of 0.05 was used to evaluate statistical significance.

Results

Tile and Watershed Discharge

Annual precipitation during the study period (2005–2012) ranged from 773 mm in 2010 to 1239 mm in 2011 (Table 2). The average annual precipitation was 1004 mm, which was slightly greater than the 30-yr average precipitation (985 mm) in the watershed. Precipitation was recorded in an average of 42 events per year (Table 2). During the study period, February was the driest month, and June was the wettest month (121.6 mm) (Fig. 2A).

Mean monthly and annual tile discharge (45.3 mm) generally followed patterns in precipitation, with greater flows observed during the winter, spring, and fall compared with the summer (Fig. 2A; Table 2). Summed tile discharge ranged from 228 to 688 mm annually and averaged 345 mm over the 8-yr study (Table 2). Approximately 28% of the measured rainfall was recovered in the tile flow. Similar to tile discharge, watershed discharge tended to be greater during the winter and spring compared with summer and fall (Fig. 2A). Annual watershed discharge ranged from 310 to 767 mm (average, 508 mm) (Table 2). Storm flow (299 mm; 59%) comprised, on average, a greater fraction of annual total watershed discharge compared with baseflow (209 mm; 41%) (Table 2). For a more detailed description of the magnitude and frequency of flows for individual tile drains and the watershed outlet, see King et al. (2014).

Because the contributing areas are different for tile drainage (319 ha) and the watershed outlet (389 ha), the ratio of tile drainage to watershed contributing area (0.82) was applied to the tile volume to calculate the contribution of tile drainage to watershed discharge. Annual watershed discharge originating from subsurface tile flow ranged from 37% in 2005 to 74% in 2010 and 2011, with an 8-yr average of 56% (345 mm × 0.82/508 mm) (Table 2). On average, annual tile discharge (283 mm = 0.82 × 345 mm) was slightly greater than annual watershed baseflow (209 mm). Tile discharge represented 47% of the mean monthly watershed discharge, and the proportion was fairly consistent throughout the year (Fig. 2A). A strong (R^2 = 0.88) relationship between watershed discharge and summed tile drainage discharge was also determined (Fig. 3A).

Phosphorus Concentration

Across all tile sites, the greatest DRP concentration measured in an individual sample was 4.64 mg L^{-1}, whereas the greatest DRP concentration at the watershed outlet was 1.74 mg L^{-1}. Annual FWM DRP concentration at the watershed outlet ranged from 0.08 to 0.16 mg L^{-1} (mean, 0.13 mg L^{-1}). Similarly, the annual FWM DRP concentration for the summed tile drainage was 0.12 mg L^{-1} (range, 0.07–0.19 mg L^{-1}). Seasonally, FWM DRP concentrations in the tile drainage were lowest in the winter, increased in the spring and summer, and tended to decline to winter values in late fall (Fig. 4A). The winter FWM DRP concentration in tile drainage was not significantly different from the spring concentration, but it was significantly less than the summer and fall concentrations (Table 3). The greatest monthly FWM tile DRP concentration (0.23 mg L^{-1}) was observed in August (Fig. 4A). In contrast to the seasonal patterns in tile drainage DRP concentration, the winter FWM DRP concentration at the watershed outlet was significantly less than spring, summer, and fall concentrations (Table 3). The greatest monthly FWM DRP concentration (0.2 mg L^{-1}) at the watershed outlet was observed in May (Fig. 4B).

The maximum measured tile flow concentration of TP was 5.48 mg L^{-1}, compared with 1.92 mg L^{-1} at the watershed outlet

Table 2. Precipitation, number of precipitation events, and annual watershed (watershed B1) and summed tile (watersheds B2, B3, B4, B5, B6, and B8) discharge. The summed tile flow column was calculated as the sum of discharge from individual tiles divided by total drained area (319 ha) within the watershed.

Year	Precipitation†	Number of events‡	Watershed baseflow	Watershed storm flow	Watershed total flow	Summed tile flow
	mm		mm			
2005	1121	40	281	328	609	276
2006	1064	42	207	260	467	228
2007	1095	47	214	305	519	265
2008	1006	42	206	405	611	462
2009	938	42	165	276	441	295
2010	773	37	138	202	340	307
2011	1239	48	303	464	767	688
2012	794	36	155	155	310	240
Avg.	1004	42	209	299	508	345

† Precipitation is a reflection of rainfall. Snowfall did occur, but no estimates of the amount of snowfall were attempted.

‡ Precipitation events are defined as any event with a cumulative precipitation amount >6.35 mm separated by at least 6 h.

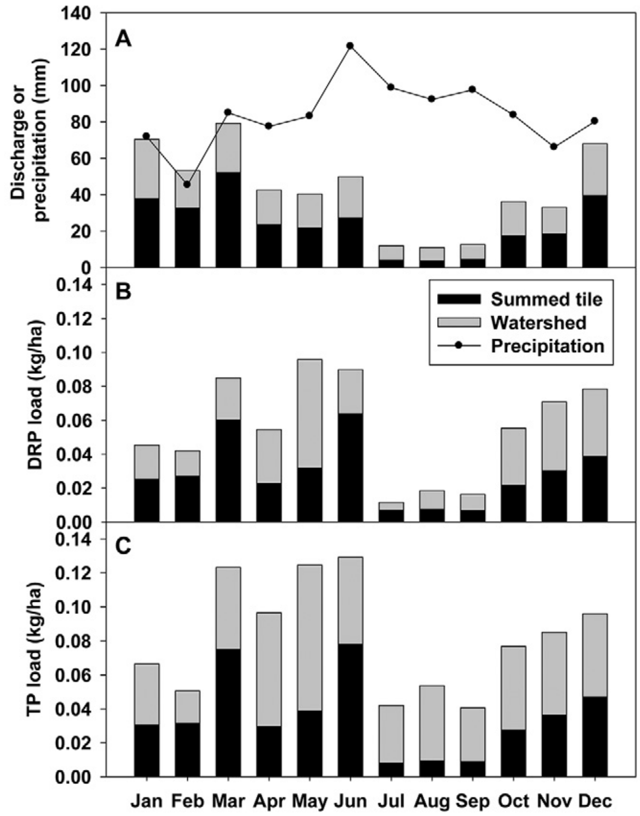

Fig. 2. Stacked bar graph illustrating the mean monthly contribution of the summed tile as a portion of the total watershed discharge (A), dissolved reactive P (DRP) load (B), and total P (TP) load (C).

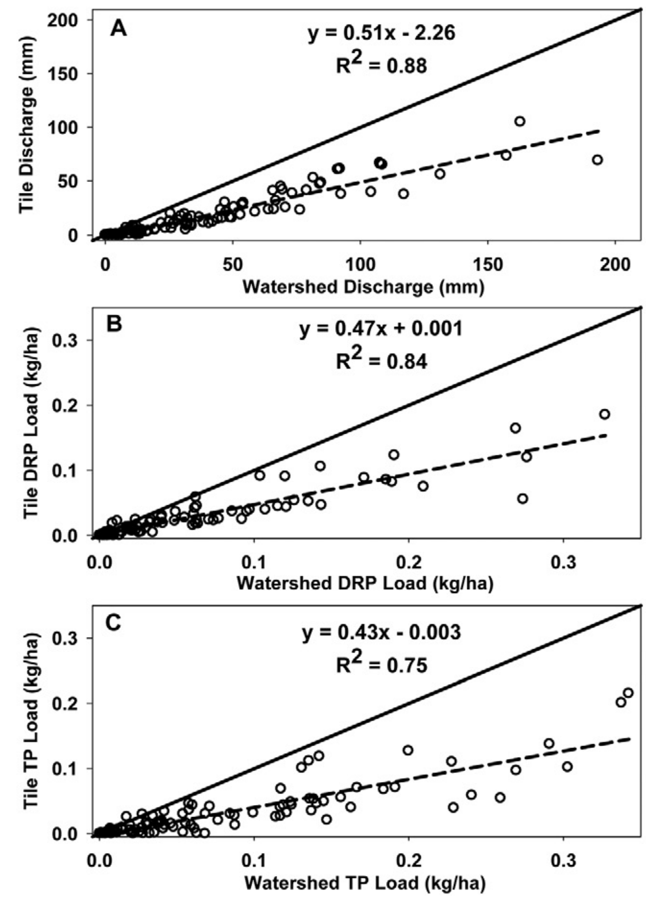

Fig. 3. Regressions of monthly (n = 96) discharge (A), dissolved reactive P (DRP) (B) load, and total P (TP) load (C) between the watershed outlet and the summed tile for the study period (2005–2012).

(Fig. 5 and 6). The annual FWM TP concentration measured at the watershed outlet ranged from 0.16 to 0.24 mg L^{-1} (mean, 0.19 mg L^{-1}). In comparison, the annual FWM TP concentration in tile drainage ranged from 0.10 to 0.23 mg L^{-1} (mean, 0.15 mg L^{-1}). The winter tile drainage FWM TP concentration (0.12 mg L^{-1}) was significantly less than all other seasons (Table 3). Similarly, at the watershed outlet, the winter FWM TP concentration was significantly less than all other seasons (Table 3). Additionally, fall FWM TP concentration at the watershed outlet was less than FWM concentrations measured in the spring and summer (Table 3). The greatest monthly FWM TP concentration in tile drainage (0.33 mg L^{-1}) was observed in August and coincided with the greatest FWM TP concentration measured at the watershed outlet (0.41 mg L^{-1}) (Fig. 4B).

Dissolved reactive P concentration measured at the watershed outlet comprised between 0 and 100% of TP concentration and averaged 55%. In contrast, 78% of the TP concentration in tile drainage was in the dissolved state. The relationship between DRP and TP illustrates for both watershed outlet (Fig. 5A and 5B) and tile sites (Fig. 5C and 5D) that greater variability exists with lower concentrations. Duration curves for DRP and TP concentration were plotted for tile drainage and the watershed outlet to determine the frequency with which concentrations were exceeded. Greater than 90% of all DRP and TP concentrations measured in tile drainage and watershed discharge exceeded recommended (0.03 mg L^{-1}) concentrations to prevent eutrophic conditions and harmful algal blooms (Fig. 6). Tile drainage DRP and TP concentrations increased with increasing discharge rates (Fig. 7). The greatest DRP and TP

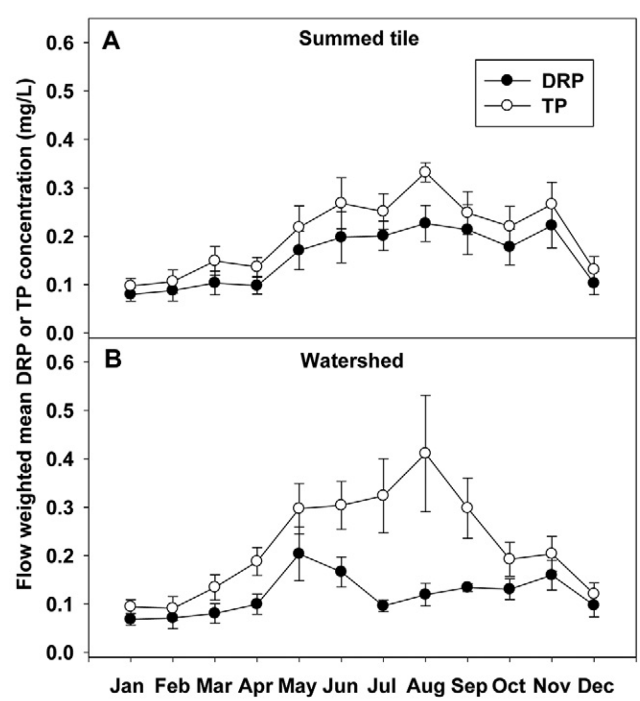

Fig. 4. Flow-weighted mean monthly dissolved reactive P (DRP) and total P (TP) concentrations for watershed (A) and summed tile (B). Error bars represent 1 SE.

Table 3. Seasonal flow-weighted mean P concentrations and P loads.

Parameter	Season†			
	Winter	Spring	Summer	Fall
	mg L^{-1}			
Concentration				
DRP‡				
Tile drainage	0.09b§	0.16ab	0.21a	0.17a
Watershed	0.07b	0.16a	0.12a	0.13a
Total P				
Tile drainage	0.12b	0.21a	0.28a	0.21a
Watershed	0.11c	0.26ab	0.34a	0.17b
Load	kg ha^{-1}			
DRP				
Tile drainage	0.13a	0.13a	0.03b	0.11a
Watershed	0.17a	0.24a	0.05b	0.20a
Total P				
Tile drainage	0.16a	0.15a	0.03b	0.14a
Watershed	0.24ab	0.35a	0.14b	0.26ab

† Seasons are defined as: winter, Jan.–Mar.; spring, Apr.–June; summer, July–Sept.; and fall, Oct.–Dec.

‡ Dissolved reactive P.

§ Values in rows followed by different letters indicate statistically significant ($p < 0.05$) differences in mean P concentration or P load.

concentrations were observed when tile flow was >0.024 mm h^{-1} (75th percentile of flow).

Phosphorus Loading

Annual DRP loads at the watershed outlet ranged from 0.33 kg ha^{-1} in 2009 to 1.26 kg ha^{-1} in 2011 (mean, 0.66 kg ha^{-1}) (Table 4). In comparison, annual DRP loading from tile drainage ranged from 0.22 to 0.69 kg ha^{-1} (mean, 0.39 kg ha^{-1}) (Table 4). Tile drainage DRP load was significantly less in the summer (0.03 kg ha^{-1}) compared with winter, spring, and fall loads (Table 3). Similarly, at the watershed outlet, summer DRP load (0.05 kg ha^{-1}) was significantly less than winter, spring, and fall loads (0.17, 0.24, and 0.20 kg ha^{-1}, respectively). Tile drainage contributed 48% of the monthly DRP measured at the watershed outlet. Additionally, a strong relationship (R^2 = 0.84) between monthly watershed DRP and summed tile DRP was measured (Fig. 3B). The largest fraction of tile drainage DRP compared with watershed DRP loads occurred in March and June (Fig. 2B).

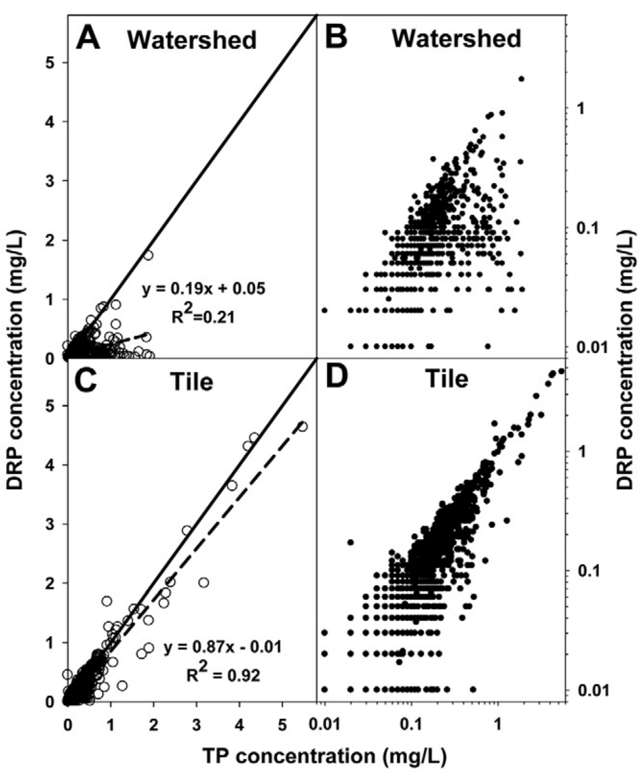

Fig. 5. Regression relationship and scatterplot between total P (TP) and dissolved reactive P (DRP) concentrations for all watershed (A and B) (n = 865) and tile (C and D) (n = 2332) concentrations measured during the study period (2005–2012).

Annual TP loading at the watershed outlet ranged from 0.52 to 1.85 kg ha^{-1} (average, 0.98 kg ha^{-1}), whereas annual tile drainage TP loading ranged from 0.28 to 0.77 kg ha^{-1} (mean, 0.48 kg ha^{-1}) (Table 4). Seasonally, summer TP loads for tile drainage and watershed discharge were significantly less than spring loads (Table 3). Monthly TP loads in tile discharge accounted for 40% of the monthly watershed TP loads, and the relationship between monthly TP loads was fairly strong (R^2

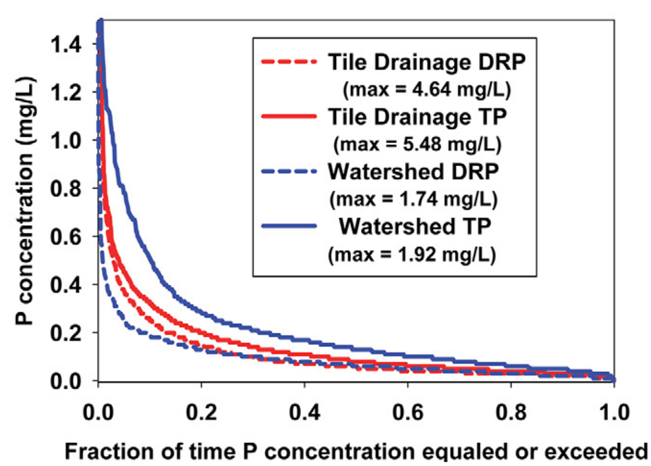

Fig. 6. Exceedance probability plot for watershed and tile drainage dissolved reactive P (DRP) and total P (TP) concentrations.

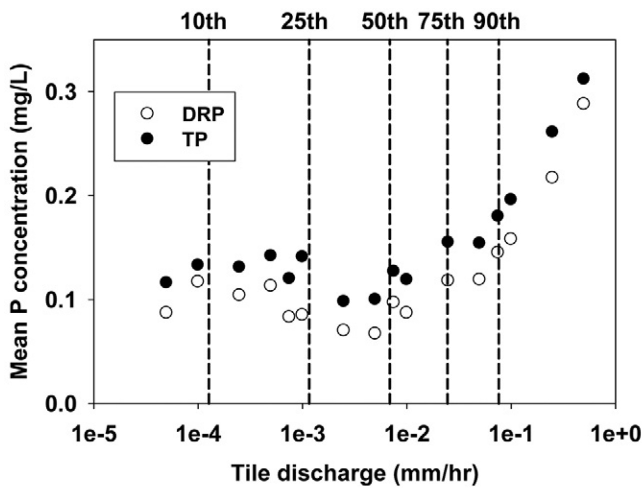

Fig. 7. Relationship between discharge and tile P concentration for all tile sites within the Upper Big Walnut Creek (UBWC) watershed. Tile flow percentiles are shown across the top of the figure. DRP, dissolved reactive P; TP, total P.

= 0.75) (Fig. 3C). Similar to DRP, the largest fraction of tile drainage TP load compared with watershed TP load occurred in March and June (Fig. 2C).

Discussion

Contribution of Tile Drainage to Watershed Phosphorus Export

An 8-yr study was conducted to evaluate the effect of tile drainage on watershed discharge and P export. Tile drainage was shown to be a significant source of water and P at the watershed scale. Few studies have simultaneously measured discharge and P loads at field and watershed scales. A comparison between this study and other field- or watershed-scale research suggests that the relationships observed between tile drainage and the watershed outlet in the current study are likely relevant for many systematically tile-drained agricultural headwater watersheds across the midwestern United States.

Tile drainage and watershed discharge in watershed B responded to precipitation events similar to those reported in the literature. Logan et al. (1980) monitored tile-drained fields across the midwestern United States and found that tile discharge expressed as a fraction of precipitation was 13, 17, and 26% in Iowa, Minnesota, and Ohio, respectively. They showed that precipitation recovery from individual tile drains can range from 0 to 66%. At the watershed scale, Owens et al. (2008) reported that 46% of precipitation was recovered at the outlet of a 1.2-km^2 headwater watershed in Ohio, which was similar to findings from watershed B (50%). In general, as watershed size increases there is a greater potential for water storage (i.e., groundwater recharge, longer flow pathways), which can affect watershed response (Tomer et al., 2003; Schilling and Zhang, 2004). Tile drainage has also been estimated to equal half of annual watershed discharge. For instance, 42% of watershed discharge was from tile drainage in a headwater watershed in Ontario, Canada (Macrae et al., 2007). Culley and Bolton (1983) extrapolated results from 12 field plots and estimated that 60% of watershed discharge in the Big Creek watershed originated from tile drainage. Differences in watershed drainage intensity likely influence tile drainage contributions to streamflow (Kennedy et al., 2012).

Surface runoff originating in watershed B was observed only during large precipitation events or during periods when the soil was frozen; thus, tile drainage was the primary pathway for P delivery. Mean annual DRP and TP loads in tile drainage in watershed B were 0.39 and 0.48 kg ha^{-1}, respectively. These loads are comparable to annual tile loads (0.38 kg ha^{-1} DRP) reported for continuous corn on a Brookston clay loam in Ontario, Canada (Gaynor and Findlay, 1995) and for a corn–soybean rotation (0.24 kg ha^{-1} DRP and 0.50 kg ha^{-1} TP) in Illinois (Gentry et al., 2007). In contrast, tile drainage TP loads in watershed B were considerably less than the 1.55 kg ha^{-1} TP loads measured from a clay loam field with a corn–soybean rotation in Quebec, Canada (Eastman et al., 2010).

Nutrient transport in crop production systems is driven by discharge (e.g., Williams et al., 2014); however, soil type can also affect P movement into the subsurface drainage network (Beauchemin et al., 1998). Soils with greater clay content are more prone to developing preferential flow paths and have a greater risk of losing P to the subsurface drainage network (Eastman et al., 2010; Simard et al., 2000). The Pewamo clay

Table 4. Annual watershed (watershed B1) and summed tile (watersheds B2, B3, B4, B5, B6, and B8) dissolved reactive phosphorus and total phosphorus loads.

Year	Dissolved reactive P			Total P		
	Watershed	Summed tile†	Fraction contributed to watershed‡	Watershed	Summed tile	Fraction contributed to watershed†
	kg ha^{-1}			kg ha^{-1}		
2005	0.57	0.23	0.33	1.16	0.35	0.24
2006	0.67	0.30	0.36	1.00	0.38	0.31
2007	0.65	0.26	0.32	1.16	0.39	0.28
2008	0.89	0.60	0.69	1.11	0.77	0.69
2009	0.33	0.22	0.55	0.52	0.28	0.44
2010	0.44	0.36	0.68	0.54	0.43	0.65
2011	1.26	0.84	0.55	1.85	0.92	0.41
2012	0.50	0.28	0.46	0.53	0.29	0.45
Avg.	0.66	0.39	0.49	0.98	0.48	0.43

† The summed tile column was calculated as the sum of P loads from individual tiles divided by total drained area (319 ha) within the watershed.

‡ Fraction contributed to watershed is equivalent to the summed tile value divided by the watershed value multiplied by the contributing area ratio (319/389 or 0.82).

loam, which comprises 46% (Table 1) of the watershed area and nearly 60% of some tile drainage contributing areas, would be more likely to develop preferential flow paths and potentially transport more P to the subsurface drains than the Bennington silt loam.

Using a similar approach to the current study, Macrae et al. (2007) evaluated the relationship between tile drainage and watershed P loads. The authors reported that significant in-stream P retention occurred and that it was a critical process in estimating the contribution of tile drainage to the watershed outlet. In watershed B, annual FWM DRP concentrations were similar between tile drainage (0.12 mg L^{-1}) and the watershed outlet (0.13 mg L^{-1}), suggesting that the capacity of the drainage ditch to attenuate DRP may be exhausted. Agricultural drainage ditches have been shown to attenuate P and buffer downstream loads (Sharpley et al., 2007; Smith and Pappas, 2007); however, the capacity is finite, and once at equilibrium, the ditch cannot assimilate additional P (Needelman et al., 2007). Indeed, a dredged agricultural drainage ditch in Indiana responded as a P sink for only 2 yr (Smith and Huang, 2010). There are no records of when the last ditch dredging occurred in the immediate study, further suggesting that the ditch sediments may be saturated and unable to attenuate additional P exports.

Managing Phosphorus in Tile Drained Watersheds to Meet Critical Levels

Dissolved reactive P and TP concentrations measured in tile drainage and at the outlet of watershed B exceeded recommended (0.02–0.03 mg L^{-1}) (Sharpley et al., 2003) and established values (0.03 mg L^{-1}) (Environment Canada, 2004) in >90% of the water samples collected in this study. Similar P concentrations to those measured in watershed B have been reported for tile-drained agricultural fields and agricultural watersheds throughout the midwestern United States and Canada (Logan et al., 1980; Algoazany et al., 2007; Kinley et al., 2007). Because elevated P concentrations are such a pervasive water quality problem, if recommended P concentrations are made standard in the United States, then the economic impacts on agricultural crop production may be insurmountable. However, once manifested, the cumulative downstream effects of elevated P concentrations can be detrimental to freshwater systems (Sharpley et al., 2003).

The challenge in managing P in tile-drained watersheds is balancing the cost of environmental improvement and the costs associated with crop production. For example, in watershed B, producer surveys indicate that annual P applications to corn are between 50 and 60 kg elemental P ha^{-1} (King et al., unpublished data, 2014). The proportion of crops grown in the watershed is roughly divided equally between corn (45%) and soybean (55%) in any given year, so the weighted P application rate to fields in the watershed is approximately 25 kg elemental P ha^{-1}. Average annual DRP loads measured in tile drainage were therefore equivalent to only 1.6% of the applied P. Algoazany et al. (2007) reported similar findings in Illinois, where DRP loads in tile drainage from four fields represented 0.3% of the P applied. Phosphorus losses of this magnitude cost a producer approximately \$1.00 per acre. Compared with the cost of P fertilizer, any proposed edge-of-field (e.g., buffer, filter strip) or end-of-tile (e.g., drainage water management structure) management practice would be much more expensive. However, P losses of this magnitude are substantial from a water quality perspective. It is estimated that the amount of P responsible for the harmful algal blooms and nuisance algae in the western Lake Erie Basin, when averaged over the total cropland area, is 0.6 to 1.1 kg ha^{-1} (Ohio P Task Force, 2013). Thus, balancing environmental impact with productivity goals should remain a focal point of future conservation management.

A recent publication from the Ohio P Task Force recommended that a 40% reduction in spring P loading would be required to minimize the magnitude and frequency of harmful algal blooms in the western Lake Erie Basin (Ohio P Task Force, 2013). Results from this study and others show that approximately half of P losses in agricultural headwater watersheds can be attributed to tile drainage and that P concentrations and loads in tile drainage are generally greater in the spring compared with other seasons. Elevated DRP and TP concentrations in drainage water during the spring coincided with the timing of P application and high discharge volumes. This indicates that adjusting nutrient management practices and controlling tile discharge through drainage water management may have the potential to decrease spring P loading and reach P reduction goals. For instance, decreasing P application rates (e.g., Philips et al., 1981) and incorporating fertilizer after application (e.g., Zhao et al., 2001; Kleinman et al., 2009) has been shown to decrease P concentrations in tile drainage. Similarly, using drainage water management during the winter and early spring can decrease P loads by 60 to 83% (Cooke et al., 2004).

Conclusions

Results of this long-term watershed study illustrate that in tile-drained watersheds, contributions of P from tile drainage to watershed P export are significant. In these watersheds, the greatest opportunity to mitigate P loads in tile drainage is in the late fall, winter, and early spring, when most of the P loading occurs. To meet nutrient reduction goals in receiving surface waters, adjusting nutrient management practices and implementing practices such as drainage water management provide the greatest opportunity to decrease P delivery via tile drainage. The development and implementation of best management practices must continue to consider surface and subsurface loss pathways as well as the balance between agricultural production economics and environmental benefits.

Acknowledgments

The authors thank the land owners and operators within the watershed who provided access to the data collection sites and management records; Larry Ufferman, Ed Miller, and Bret Bacon (DSWCD) for helping to identify cooperators, collecting the management data, and developing a database of management records; Eric Fischer for analytical expertise; and Ginny Roberts, Jeff Risley, Sarah Hess, Ann Kemble, and Phil Levison for help in data collection and site maintenance.

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